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This report discusses a Broadband Bionic Sonar System and a signal processing technique for detection and identification of underwater targets. Since the sonar and radar target echoes are the solutions to the same Helmholtz Equation in their respective media, an Ultra Wideband Radar System can also be developed for target detection and identification base on the same principles and signal processing techniques. In the bionic sonar system with the resonance detection technique for detection and identification of underwater targets, it appears to mimic a dolphin's and/or a bat's acoustic sensory systems. It is onceivable that an Ultra-Wideband Radar System of the same detection technique can also be developed.

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Broadband (Ultra Wideband) Sensor System
for
Active and Passive
Detection and Classification of Targets

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Final Report 1 of 2 for the period
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Introduction

This report discusses a successful investigation of a Broadband Bionic Sonar System and a signal processing technique for detection and identification of underwater targets. Since the sonar and radar target echoes are governed by mathematical solutions to the same Helmholtz Equation in their repective media of water and air, an Ultra Wideband Radar System can also be developed for target detection and identification base on the same principle of resonance and signal processing techniques. The bionic sonar system employs the resonance detection technique for detection and identification of underwater targets. It appears to mimic a dolphin's or a bat's acoustic sensory systems. Conceivably, an Ultra Wideband Radar System of the same detection technique can also be developed.

The dolphin's sonar system transmits a very short broadband pulse. It detects and classifies a target by processing the modulation of the echo's (back scattering) broadband spectrum. This spectral modulation is directly related to the target's natural resonance. Using the G-Transform technique and over the past few years, the author has successfully showed that target resonance exists and it is unique to target's size, shape, structure and material composition. Furthermore, this natural resonance exists in both (active sonar) acoustic echoes, back scattering and (passive sonar) acoustic scattering in acoustic noise background. Using trained neural networks, these targets' resonances/signatures can be correctly identified for the respective targets. It is conceivable that the same techniques can be applied to a broadband (Ultra Wideband) radar system, similar to a dolphin's broadband sonar system. Thus a ultra wideband radar system can be developed for target detection and identification.

A variety of experimental results over the past decades indicates that dolphins possess a highly sophisticated broadband sonar system. This broadband sonar system is highly adaptive in detecting, discriminating and recognizing objects in a reverberating and noisy environment. Furthermore, recent experiments indicate that using the same detection technique, underwater targets are detectable and identifiable in "acoustic daylight" or acoustic background noise. This seems to suggest that the dolphin's approach to target detection and recognition is based on resonance and resonant scattering of targets. This broadband detection method based on Natural Resonance and Resonant Scattering Theory was presented at SPIE Conferences for the past few years[9-14]. Using the G-Transform, acoustic echoes from differently shaped targets have unique transformed signatures. These unique signatures used as inputs to a trained neural networks have been successfully demonstrated in detecting and identifying underwater mine and minelike targets. This paper is divided into six parts. Part II presents the dolphins' bionic sonar system. Part III describes the G-Transform, its purpose and its usefulness in presenting the unique characteristics of targets. Part IV defines resonance and resonant scattering. Part V describes the active and passive experimental results of target detection and identification. Part VI presents the results and conclusions.

Bionic (Dolphin) Sonar System

Dolphins possess a unique sonar system. It was reported that the dolphin's head serves as an acoustic lens[1]. The transmitted pulse is focused to a narrow beam of approximately twenty (20) degrees as it is passed through the head of a dolphin. The dolphin transmits a very short sinusoidal like pulse as diagrammed in figure 1-a. It is only 50 micro-seconds long. The frequency composition of the transmitted pulse is a broadband signal centered at 120kHz as diagrammed in figure 1-b. Figure 1-c is the "Phi" domain representation of this transmitted pulse. Figure 1-d is a 3-D, time-frequency presentation of this transmitted pulse. It is a short-time FFT of a sliding windows of 30 micro-seconds long

transmitted pulse of figure 1-a. It is interesting to note that the frequency content of each of the sliding windows is the same. In other words, the transmitted pulse is a broadband pulse at all times. Careful examination of figure 1-d indicates that the energy level is also constant over the entire pulse. Figure 1-e is the "phi" domain presentation of the transmitted pulse. The dolphins analyze the return echoes or back scattering from the targets. From figure 3, one can observe the variations in time domain and "phi" domain presentations of four typical echoes from four cylinders. These cylinders are of the same size but made of different materials - steel, aluminum, bronze and glass. Dolphin experiments have shown that these variations can be differentiated by the dolphins even when background noise is added to the echoes. Theoretically, the variation is the result of the natural resonance of these targets. These resonances are directly related to the scattering solution of the Helmholtz Equation as reported by many authors in the references. Thus, possibly, dolphins are able to detect and identify targets by resonance.

Resonant Radiation & "G" Transform

Based on 17 of the 21 references, it is clear that underwater targets respond to acoustic excitation. It appears that underwater targets respond to narrow band frequency excitation as shown theoretically by Gaunaurd, Uberall, etc.[8] and experimentally demonstrated by Tsui and Reid[16]. These narrow band frequency responses show that the targets resonate at the nulls of these frequency spectrums. Targets also respond to broadband frequency signals[10-14]. These responses appear as modulations on the frequency spectrums of the echoes. These resonant responses also appear as nulls on the broadband spectrum. Some of the authors[2,5,20,21] show this resonant modulation as nulls in the wave numbers. In the case of a dolphin sonar, these resonant responses appear as modulations to the transmitted spectrum[1,10-14]. Thus, the target interacts with each frequency component in the band differently. Since target resonance is determined by its dimensions, shape, material composition, and structure, the frequency modulation is unique to the target in terms of size, shape, material, etc. Thus, characteristic

information about a target appears in the spectral domain of the target's echo. G-Transform was found to be a simple and efficient process to present this information as shown by the author[10-14]. Mathematically, G-Transform is a triple forward Fourier Transform of time signal, S(t), as shown in equation (1) below:

$$\mathbf{S}(\ \varphi\ ) = \mathbf{FFT}\ \{\ \mathbf{FFT}\ [\ \mathbf{FFT}\ (\ S(t))\ ]^{2}\ \}^{2}\ . \qquad (1)$$

But, S(w) is the Fourier transform of the S(t) which is:

$$S(w) = \mathbf{FFT}\ (\ S(t)). \qquad (2)$$

Therefore, $S(\varphi)$ can be written as

$$\mathbf{S}(\ \varphi\ ) = \mathbf{FFT}\ \{\ \mathbf{FFT}\ [\ S(w)\ ]^{2}\ \}^{2} \qquad (3)$$

or $S(\varphi)$ is the auto-correlation of the [S(w)] below:

$$\mathbf{S}(\ \varphi\ ) = \textbf{Auto-Corr.}\ \{\ [\ S(w)\ ]\ \} \qquad (4)$$

From mathematics, the auto-correlation of a time domain signal, S(t), is "tau" domain, $S(\tau)$. Then, the auto-correlation of a frequency domain signal, S(w), was named "phi" domain, $S(\varphi)$. If Cepstrum is defined as the Fourier transform of the Auto-Correlation of the time signal, S(t), then G-Transform may not be Cepstrum. Then, possibly, G-Transform is a modified Cepstrum of the time signal, S(t).

Why the G-Transform? Studies[10] show that a time echo, S(t), from a target varies from echo to echo. Even consecutive echoes from the same target are different. Thus the Fourier Transform of these echoes also varies from echo to echo. However, in the "phi" domain, $S(\varphi)$, these consecutive echoes from the same target remain the same. Thus, in the "phi" domain, targets have unique signatures based on the target's size, shape, etc. Using a trained Back-propagation Neural Networks[9] with 30-input nodes, 8-hidden layer nodes and four (4) output nodes and over 500

test target echoes for each aluminum, bronze, glass, and steel cylindrical targets, no error was detected.

Resonance and Resonant Scattering

Over the past decades, many broadband (dolphin) sonar experiments have been conducted demonstrating that dolphins possess a superior sonar system. They can detect, discriminate and recognize object structures, shapes, sizes and material compositions with 85-90% accuracy. Other animals such as blue whales, seals, and bats also possess unique biological sonar systems which are highly adapted to their environments. Using their sonar systems, these sea mammals can range and identify characteristics of submerged objects by transmitting a broadband signal and processing the returned echoes from these objects[1]. Using trained neural networks to recognize these target echoes in the frequency domain, bionic sonar systems mimicking these mammals were designed and successfully demonstrated. However, how these mammals exactly detect and identify targets is still a mystery.

The scattering theory of structures has been investigated[3-8,15-18] for many decades. These studies have resulted in the theoretical development of scattering of elastic spheres in liquid[20] and ray trace technique[21]. The authors simulated the acoustic echoes from an elastic smooth shell in water. Using the Ray Trace technique, they contributed to the understanding of the mechanism of this elastic wave propagating in an elastic shell. They also contributed to the understanding of radiation or scattering of this acoustic energy from the shell to surrounding media. In this paper, this radiation from the elastic shell is referred to as resonance and resonant scattering. A collaborated investigation with Yang showed perfect concurrence of the measured data with the calculated exact solution of a dolphin acoustic echo from a 3-inch air-filled, 24 gage, stainless steel sphere. In this study, a dolphin acoustic echo, figure 2-a, contains the two components which can be separated into the specular reflection component, figure 2-c, and the resonant or back scattering component, figure 2-b. In an acoustic echo, the frequency

composition of a resonant scattering component is different from the frequency component of a reflection component as shown in figures 2-e and 2-f, respectively. Although they are of the same band width (same as the transmitted bandwidth), the modulation on their frequency spectrums is different. In figure 2-f, the frequency spectrum of the specular reflection is identical to the transmitted signal. Figure 2-e shows a strong modulation of the spectrum of transmitted signal. One observes that specular reflection, figure 2-j, is the same as the G-Transform of the transmit signal. Whereas, figure 2-h shows the resonant component with a unique characteristic signature. From Yang's Ray Trace simulation, the resonant component is the same back scattering energy radiated from the air-filled steel spherical shell into the water.

Active and Passive Acoustic Experiments and Results

Active Acoustic Experiments

The active sonar experiments were conducted in a 10 foot diameter tank. A broadband acoustic transducer is suspended near the center of the tank, while, the test targets are located a meter in front of the transducer. The transducer transmits a dolphin's broadband pulse toward the target. It then receives the return echo from the target. After some signal conditioning, the target echo was digitized at 1MHz and recorded in a computer memory. Figure 3 are typical echoes of glass, steel, bronze and aluminum cylindrical targets about 2.5 inches in diameter and 6 inches long. From figure 3, one can observe the differences of the echoes in time domain signal and the G-Transformed signal. One observes the uniqueness of these signatures[11-13] due to target shapes, sizes and material compositions.

Passive Acoustic Experiments

Background noise[3], also referred to as "acoustic daylight", exists naturally in open water. This background acoustic noise is background acoustical energy. The noise is generated by wave action against the

shores, the beaches, the rocks, and the collapse of air bubbles in the breaking waves (white caps) created by wave motion. Furthermore, acoustic noise is generated by ships at sea and motor boats in the harbor. In addition, noise can be generated by sea animals such as whales, dolphins, snapping shrimps, etc. Acoustic noise energy is equivalent to light being reflected from walls, ceilings, and objects into our eyes that enables us to "see". Thus, one can image underwater[3,18] with background noise. Dr. Yang's simulation suggests that underwater object illuminated by a transmitted pulse will radiate, back scatter, at its natural resonant frequency. Thus, if a target is illuminated by background noise, it will also radiate at it natural frequency. Thus, underwater objects can be detected by its resonant radiation in background noise. Since no pulses were transmitted, the system is a passive sonar system. The system's hydrophone just "listens" for object resonance in the background noise.

The passive experiments were conducted on a 10' X 20' floating platform (a floating dock) in one of many coves off a very small island in Kaneohe Bay, HI. The cove faces the inside of the bay where there is no direct ship noise into the cove from the open waters. Most of the noise is generated by wave action against the rocks and shoreline in the bay. There were occasional noises from snapping shrimp and dolphins. Many experiments were conducted on the edge of the deck with a "SonoPanel", a broadband planar acoustic sensor. A 2.5 inch diameter aluminum cylinder, and a 3 inch, a 6 inch, and a 12 inch diameter stainless steel sphere targets were placed in front of the sensor for these noise measurements. Measurements were recorded before and after each cylinder was placed in front of the sensor. Results were recorded and processed. Figures 4 & 5 are diagrams of these detectable resonances in the background noise. It is clear that some resonant scattering is present and corresponds to the natural resonance of these targets. In another experiment, the resonance from the same 3 inch diameter stainless steel sphere was detected when the sphere was placed on the muddy bottom and was buried in the muddy bottom. These results along with resonant detection in acoustic daylight results will be submitted to JASA for consideration in a future publication.

Conclusion

Having investigated the broadband (dolphin) sonar system, it appears there are many advantages to a broadband system over a narrow band system. In an active sonar system, the broadband system can echolocate a target equally as well as a conventional narrow band system. From our study and Yang's simulation, it is clear that the target echo contains two parts, the specular reflection and back scattering parts. The specular reflection is the mirror image of the transmitted signal which is the stronger part at the beginning of the return echo. This is very useful in echolocation. The back scattering part contains the characteristics of the target in the form of modulations on the broadband transmitted spectrum. These modulations on the broad frequency spectrum are attributed to target shape, size, structure and material composition. This frequency modulation appears to be the natural resonance of the target as shown in Yang's computer simulation. Based on the success in background noise experiments, this frequency modulation also exists in a passive broadband sonar system where the illuminator is the background noise, "Acoustic Daylight", in the water. The modulation of the background noise spectrum was observed from underwater spheres and cylinders. This seems to indicate that underwater targets resonate at its natural frequency. Since these frequency modulations are unique to the targets, the G-transform of these modulations is also unique to the targets. Thus, these transformed target signatures can be used as input to a "trained" neural networks for target recognition/identification.

From the studies, it is clear that the broadband (dolphin) sonar system has many advantages over the narrow band system. They are:

1. equally effective in target echolocation,

2. superior in target identification,

3. superior in detecting a target in a noisy environment,

and 4. consistently capable in detecting a target in acoustic background noise.

The ability to detect a target in background noise is vital in underwater surveillance and harbor security. Conversely, a "bottomed" submarine is no longer safe because it is detectable in background noise. Furthermore, Baum[2] and Gaunaurd and Uberall[7] showed that a broadband sonar echo is similar to that of a radar echo. Mathematically, these echoes are solutions to the Helmholtz Equation in a different media. Thus, the technique for broadband sonar target detection and identification can easily be adapted to a broadband radar system. Most importantly, as suggested in Baum[2], a library of target aspects to a radar system can be developed for target identification using pattern recognition techniques or neural networks. It is true that the sonar echoes and radar echoes are solutions to the same Helmholtz Equation in two diferent media, then similar to acoustic daylight, there exists microwave (radar) noise in the atmosphere due to natural and man made sources. These man made sources can be radio and TV station transmissions, cell and cordless phones transmissions, local and military microwave transmission systems, and other communication and radar systems transmissions, etc. The existence of radar noise is obvious; therefore, it is conceivable that a passive radar system for detection and identification can also be developed.

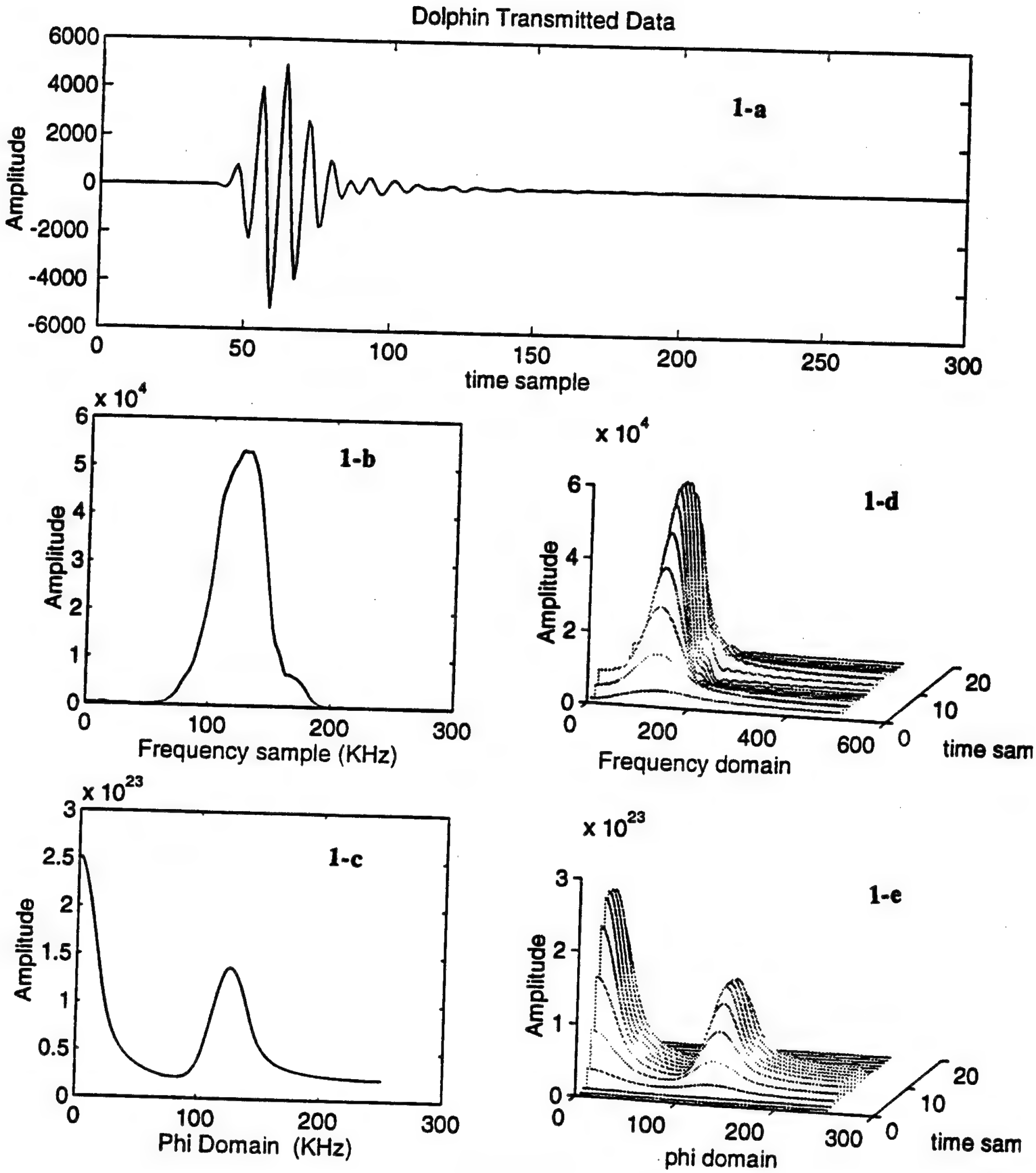

Figure 1. Transmitted Dolphin Pulse

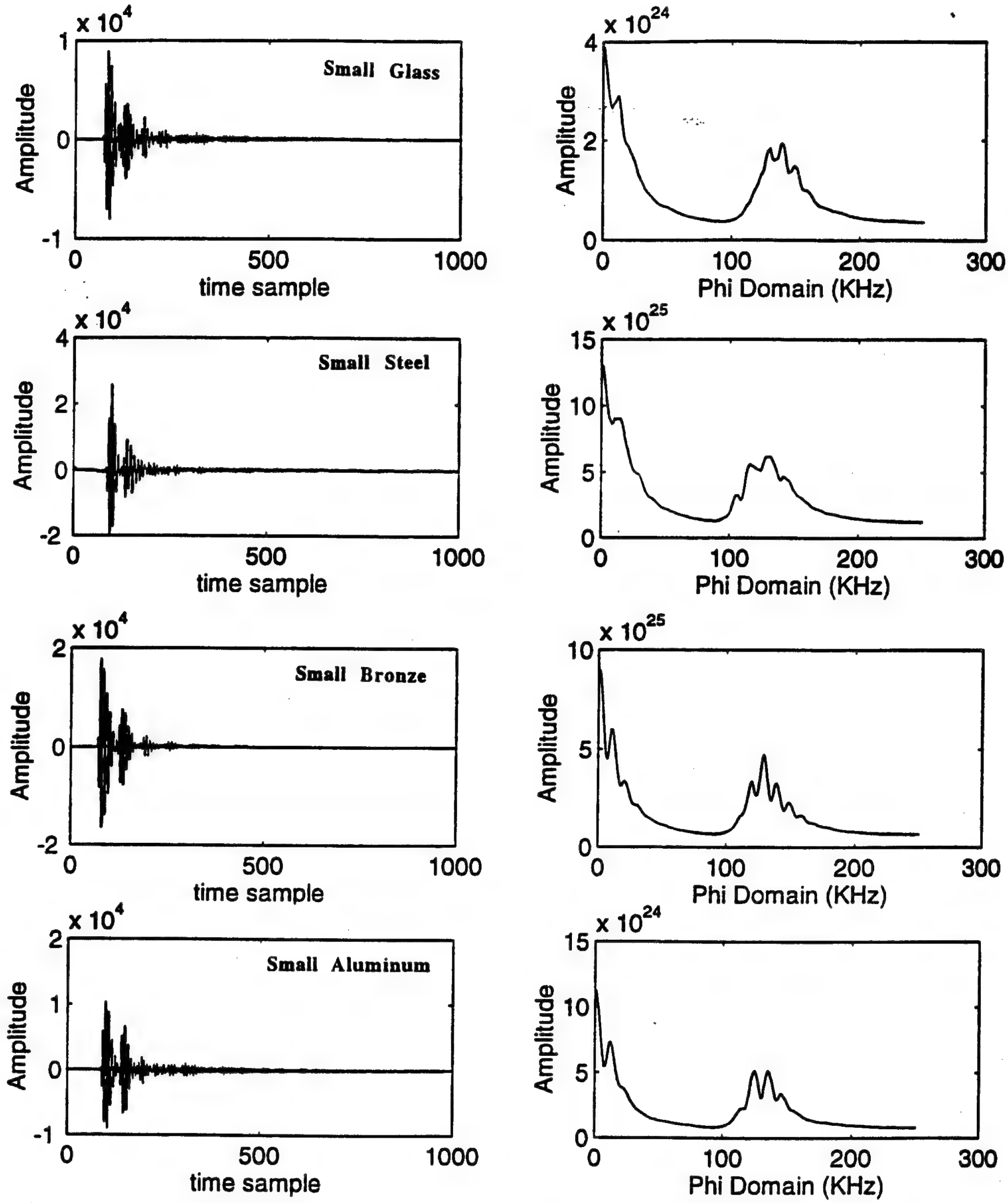

Figure 3. Typical Small Cylinder Target Echoes and Signatures

Scattering of 3-inch Air Filled Stainless Steel Sphere

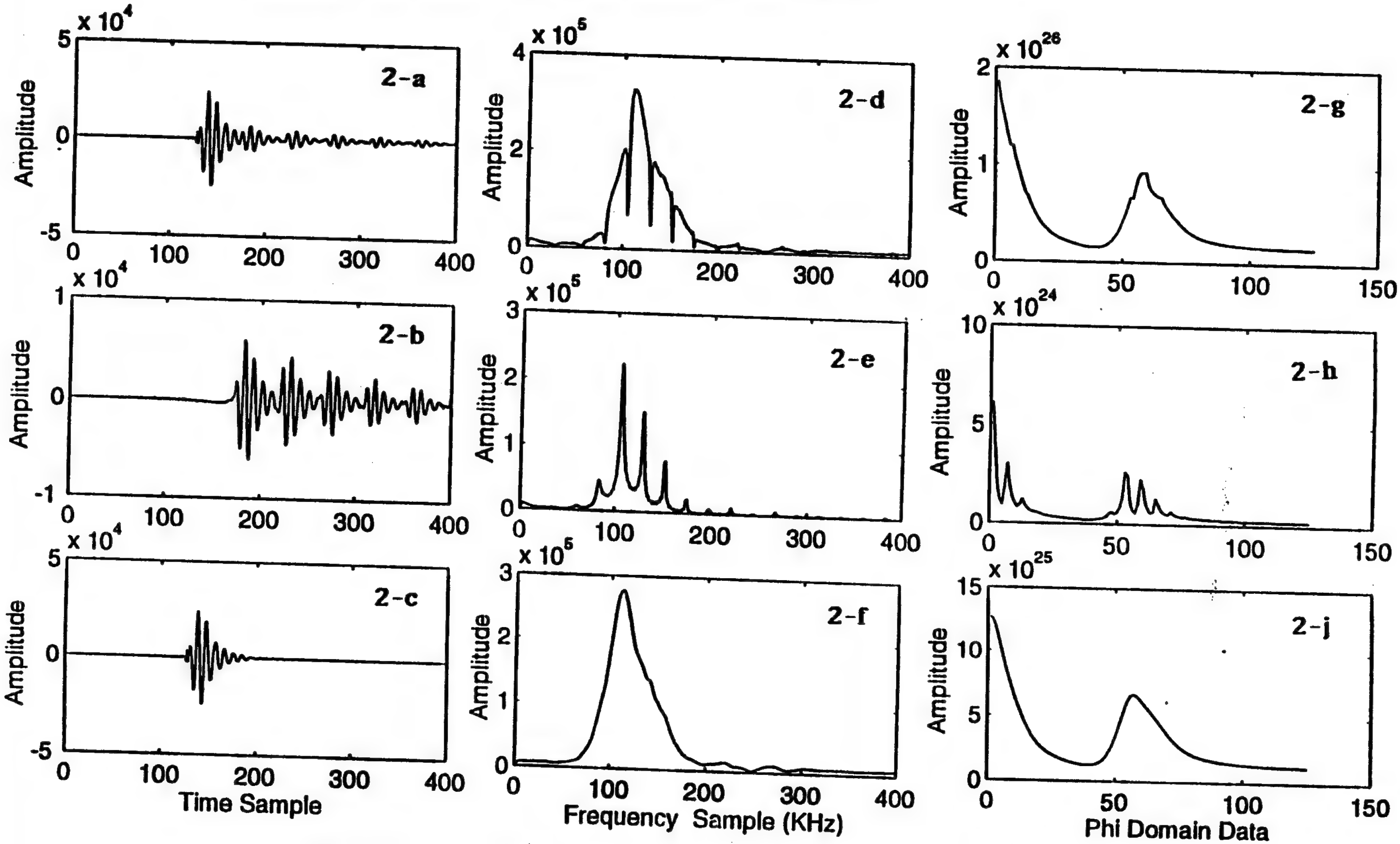

Figure 2. Echo, Scattering and Specular Reflection

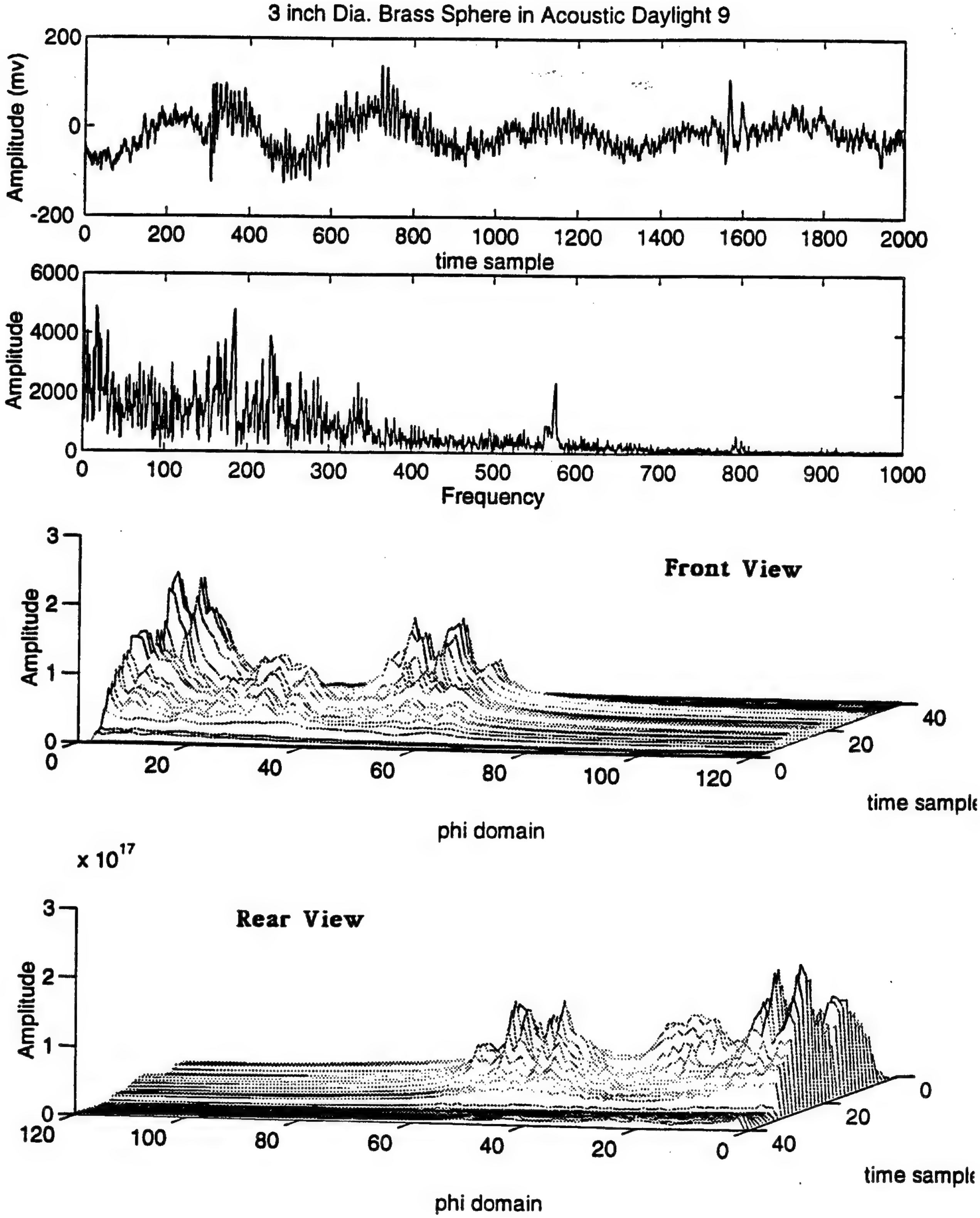

Figure 4. Scattering of 3-inch Solid Brass Sphere

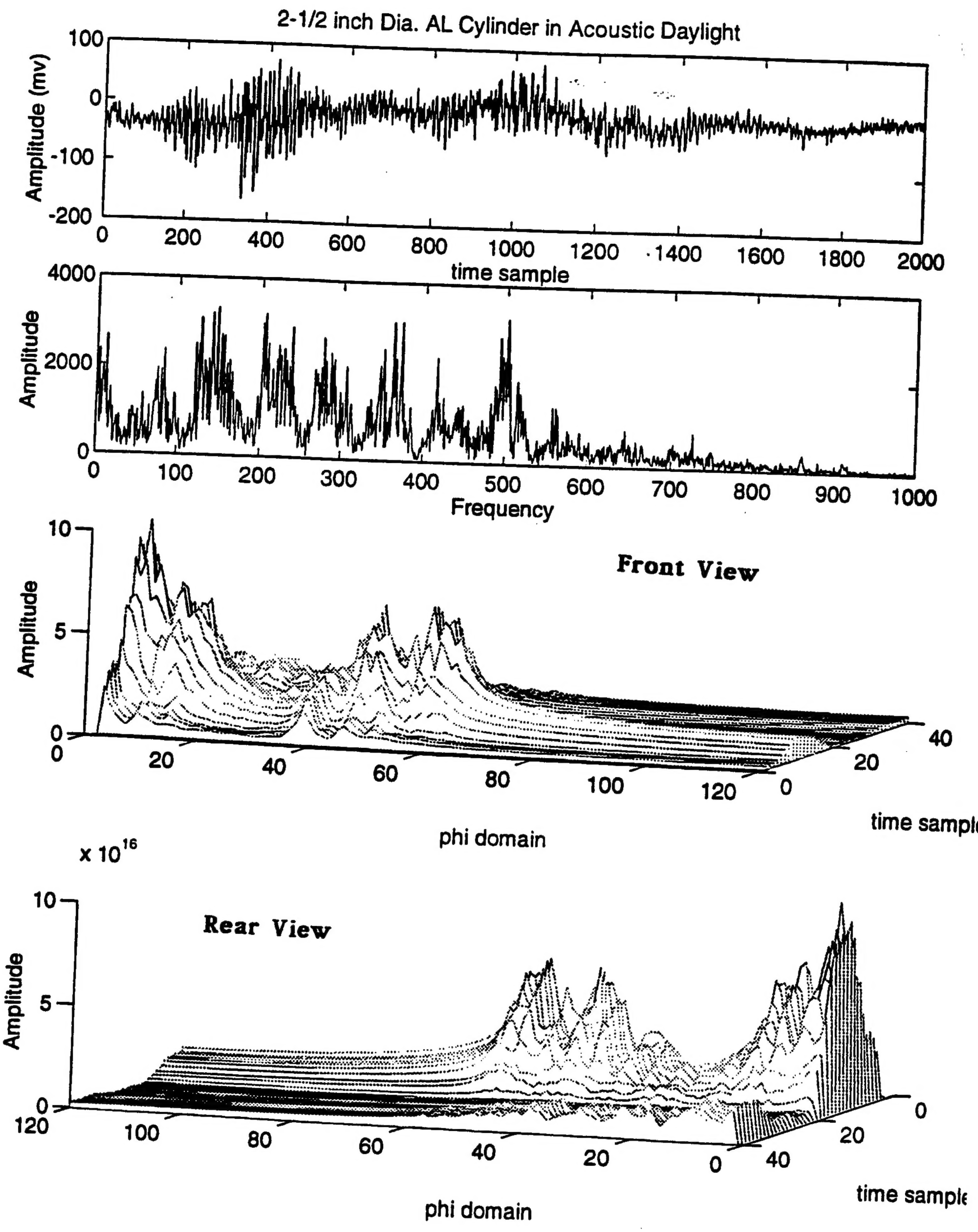

Figure 5. Scattering of 2.5-inch Dia. Aluminum Cylinder

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References

1. Au, W. W. L. & Hammer, C.E. Jr.. (1980). "Target Recognition Via Echolocation by Tursiops Truncatus" in Animal Sonar System, ed. by R.G. Busnel & J.F. Fish, (Plenum, New York), pp.855-858.
2. Baum, Carl E., (1994) "Signature-Based Target Identification and Pattern Recognition", IEEE Antennas and Propagation Magazine, Vol.36, No, 3, Jun 1994.
3. Buckingham, Potter, & Epifanio, (1996) "Seeing Underwater with Background Noise", Scientific American, Feb 1996.
4. Dragonette, LR, Vogt, RH, Flax, L, Neubauer, WG, (1974), "Acoustic Reflection from Elastic Spheres and Rigid Spheres and Spheroids. II. Transient Analysis", JASA, 55 (6), pp.1130-1137.
5. Flax, L. et al,. (1978). "Theory of Resonance Excited by Sound Scattering" JASA., 63, pp.723-731.
6. Junger, Migauel C. (1951) "Sound Scattering by Thin Elastic Shells", Journal of Acoustical Society of America, 23, pp 366-373.
7. Gaunaurd & Uberall. (1961). "Radar and Sonar can Identify Targets," MSN, pp. 108-113, April 1961
8. Gaunaurd & Uberall. (1978). "Theory of Resonance Scattering from Spherical Cavities in Elastic and Viscolastic Media," JASA, 63, pp.1699-1712
9. Goo, G. (1991) "Back Propagation Neural Networks Trained to classify Sonar Objects", The International Conference on DSP Appl. and Tech. Oct. 28-31,'91, Hotel Palace in Europa Center, Berlin, Germany.
10. Goo, G & Au, W, "Bionic Sonar for Classifying Sonar Targets", SPIE AeroSense'95, Session on Detection Technologies for Mines and Minelike Targets, Marriott's World Center, Orlando, FL. Apr. '95.
11. Goo, G & Au, W., (1996), "Detection and Identification of Buried Objects in Shallow Waters", SPIE AeroSense '96, Session on Detection Technologies for Mines and Minelike Targets II, Marriott's World Center, Orlando, FL. Apr. 1996.

12. Goo, G & Au, W., (1997),"Detection and Identification of Underwater Objects with 'G'-Transform", SPIE AeroSense '97, Session on Detection and Remediation Technologies for Mines and Minelike Targets III, Marriott's World Center, Orlando, FL. Apr. '97.
13. Goo, G. (1997),"Detection and Identification of Underwater Objects in Background Noise, Acoustic Daylight", SPIE AeroSense '97, Session on Automatic Object Recognition VII, Marriott's World Center, Orlando, FL. Apr. 1997.
14. Goo, G. et al,"Detection and Identification of Underwater Objects in 'Acoustic Daylight', Background Noise", SPIE AeroSense '98, Session on Detection and Remediation Technologies for Mines and Minelike Targets IV, Marriott's World Center, Orlando, FL. Apr. '98.
15. Hickling, Robert(1962) "Analysis of Echoes from a Solid Elastic Sphere in Water", JASA, 34, pp 1582
16. Hickling, Robert(1964) "Analysis of Echoes from a Hollow Metallic Sphere in Water", JASA., 36, pp 1124
17. Maze, G. et al., (1985). "Resonance of plates and cylinders: Guided waves," JASA., 77, pg.1352-1357.
18. Potter, John R., (1994), "Acoustic Imaging using Ambient Noise: Some Theory and Simulated Results", JASA. 95 (1), pp 21-33.
19. Tsui, Reid & Gaunaurd, "Resonance scattering by elastic cylinders and their experimental verification" JASA, June1987.
20. Yang, Y., Norris, A.N., & Couchman, L.S., (1995) "Acoustic Scattering from Fluid-loaded elastic shells: A Gaussian beam Approach", JASA. 98 (1), pp 611-622.
21. Yang, Y., Norris, A.N., & Couchman, L.S., (1996) "Ray Tracing over Smooth Elastic Shells of Arbitrary Shape", JASA. 99, pp 55-64.